Principal Component Analysis of the Geochemistry of Sediments from Boreholes CRP-2 and CRP-3, McMurdo Sound, Antarctica

Senior Thesis

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Abstract

Boreholes CRP-2 and CRP-3 were drilled in seafloor sediments of McMurdo Sound, Antarctica in the late autumn of 1998 and 1999. Chemical data was recorded along with depth from the borehole. Using Past3 software, this chemical data was run through a principal component analysis to define trends in the data into new axes with the intention of eventually establishing provenance. Once the principal component analysis operation was completed the components were reviewed to find which were most significant. Three principal components were chosen and elements that defined the greatest amount of variation in each principal component were identified. The scores of the principal components were plotted against depth to display the rise and fall of the concentration of these defining elements throughout the depth of the borehole. These elements were matched to the known chemistry of source terranes on land along the West Antarctic Rift System. Principal component one was matched to the McMurdo Volcanic Group, Principal Component two was matched to the Basement rock of the region, and Principal Component three was also matched to the McMurdo Volcanic Group. When the geologic history of the region was reviewed alongside the graph, it was found that the abundance of elements attributed to the McMurdo Volcanic Group in the core mimicked the established pattern of volcanic activity in the McMurdo Volcanic Group. This evidence supported that principal component analysis can quickly and reliably be used to identify provenance in sediments.

Acknowledgments

I would like to thank Dr. Larry Krissek, without whose guidance and expertise this thesis would not have been possible, the Edmund M. Spieker Memorial Scholarship from the School of Earth Sciences for contributing toward my education and experience in the field, The Ohio State University School of Earth Sciences for helping me turn my passion into a career, Taylor Martin, whose love and encouragement gives me the strength and confidence to rise to new heights, and to my family, whose unwavering support, love, and guidance helps me grow to be the man and geologist I am.

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Introduction

Boreholes CRP-2 and CRP-3 were drilled in McMurdo Sound Antarctica in late 1998 and 1999 as part of the Cape Roberts Project, an international effort to drill seafloor core off Cape Roberts in the Ross Sea (Figure 1). The project consisted of a set of four holes drilled into dipping formations in such a manner that the holes covered over 3000 meters of stratigraphic section without needing to drill the entire depth at one location. Cores were recovered by a wireline rig set up on sea ice. The geochemical data from the fine-grained sediment recovered in the second and third holes drilled, CRP-2 and CRP-3 respectively, were collected by x-ray fluorescence techniques. Using these data and the process of principal component analysis, it is possible to determine which chemical elements contribute the most to the total variance in the data set. By comparing these elements to the chemical fingerprints of known sediment source terranes, it is possible to establish provenance.

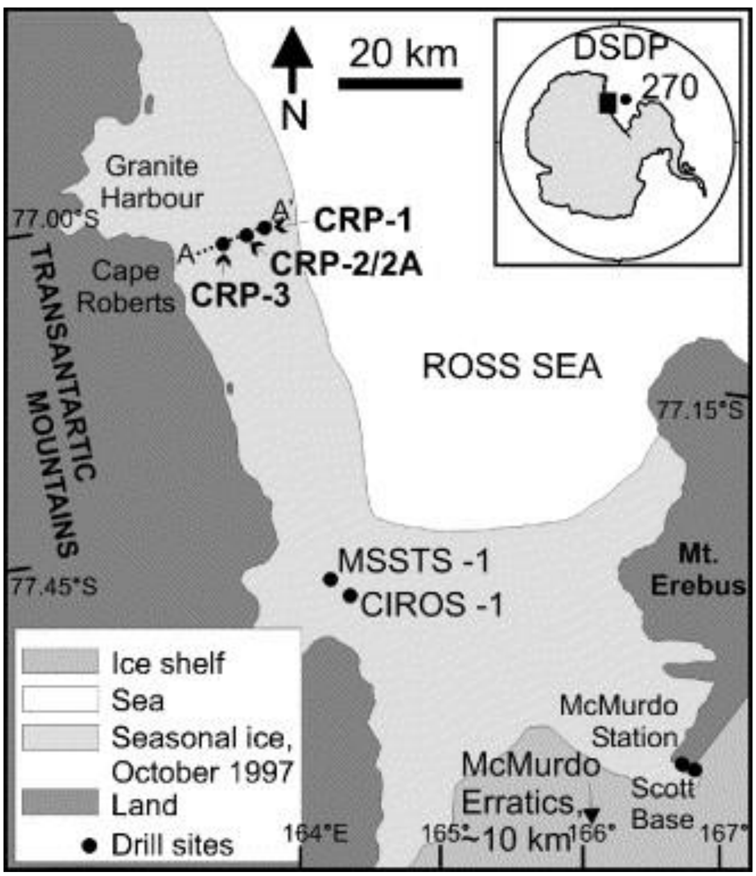

Figure 1: Location of boreholes CRP-2/2A, CRP-3 and others from the Cape Roberts Project. From Prebble et al., 2006

Methods

Seafloor cores were collected during the Cape Roberts Project from boreholes CRP-2 and CRP-3, Antarctica. Bulk chemistry of fine grained sediments was analyzed by x-ray fluorescence (XRF) for major trace elements at New Mexico Tech. (Krissek and Kyle, 2000; 2001).

The data were entered in a spreadsheet and all cells containing "%value%" were cleared to be blank for processing by Past 3.18 software. Rows missing more than two of the geochemical entries were cleared to avoid clutter. Data sets containing smoothed Al/Ti, smoothed chemical index of alteration (CIA), Nb, Rb, Sr, Pb, Zn were exported to Past 3.18 software. Chemical Index of Alteration is a tool which uses ratios of elements retained during chemical weathering versus a sum of elements retained during chemical weathering and those removed during chemical weathering to determine how much chemical weathering sediment has undergone. The data were then run through a principal component analysis, generating new principal components.

For this operation the data were highlighted. In the toolbar select the "Multivariate" option, the Ordination option of the dropdown below, then click Principal Components (PCA). This process finds linear trends in a multi-dimensional cloud of data points and defines those trends as new coordinate axes, reducing the number of dimensions describing the data space to one and simplifying the process of finding associations between variables within data.

The loadings/variance plot was inspected to determine the most important principal components. Principal components one, two, and three were determined to be the most important and accounted for over 96% of the variance in the dataset. The high percent variance determined these principal components were the focus of the study. The Scores values of the new principal components were plotted against the depth on line graph. Conclusions were drawn from the loadings plots about which geochemical components defined each of the principal components.

These geochemical components were compared to known geochemical information from source terranes on land to determine provenance. These results were compared to a previous experiment using Nb concentrations to determine provenance to see if the two studies agree.

Results

The given data from the boreholes CRP2 and CRP3 contained concentrations of elements that could be attributed to source terranes. The principal component analysis (PCA) operation created seven new principal components (PC) from these data. The PCA of the data yielded scores, or “the transformed variable values corresponding to a particular data point,” and loadings, or “the weight by which each standardized original variable should be multiplied to get the component score” for each new PC. (Shaw, 2003) The data also yielded percent variances which were defined as the portion of the total variance in the original dataset explained by each PC. This variance adds up to 100% when all PCs are combined.

With the percent variance (Figure 2) it was determined that the most important PCs were components one, two, and three. The three PCs accounted for 98.76% of variance in the seven total PC’s. PC one alone accounted for 85.26% of variance, PC two accounted for 11.41%, and PC three accounted for 2.09% of variance.

Plots of the scores of these three PCs against the composite depth of the multiple boreholes yielded a graph showing the importance of these three PCs through the stratigraphic section (Figure 3). Three more graphs were made to display the behaviors for individual PCs (Figures 4, 5, 6). With the graphs generated, the loadings plot was assessed to determine which elements were causing the greatest variation in each PC (Figures 7, 8, 9). This was found to be strontium for PC one, rubidium for PC two, and zinc and niobium for PC three. These elements are the most important driving forces for the variance represented by these PCs. Then provenance was determined by matching these important elements to the compositions of known source terranes (Table 1) (Roser and Pyne, 1989)

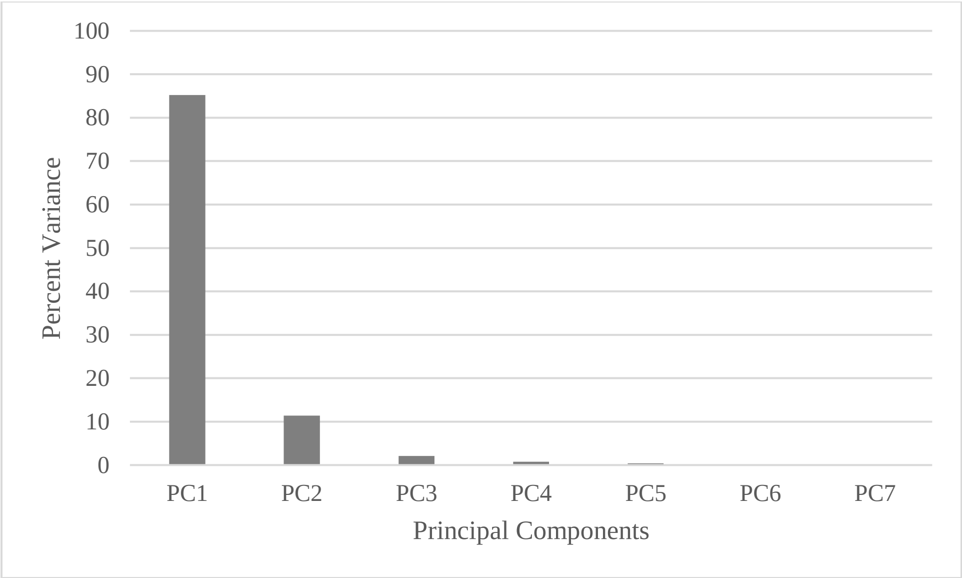

Figure 2: Percent Variances of Principal Components. PCs one, two, and three are the largest.

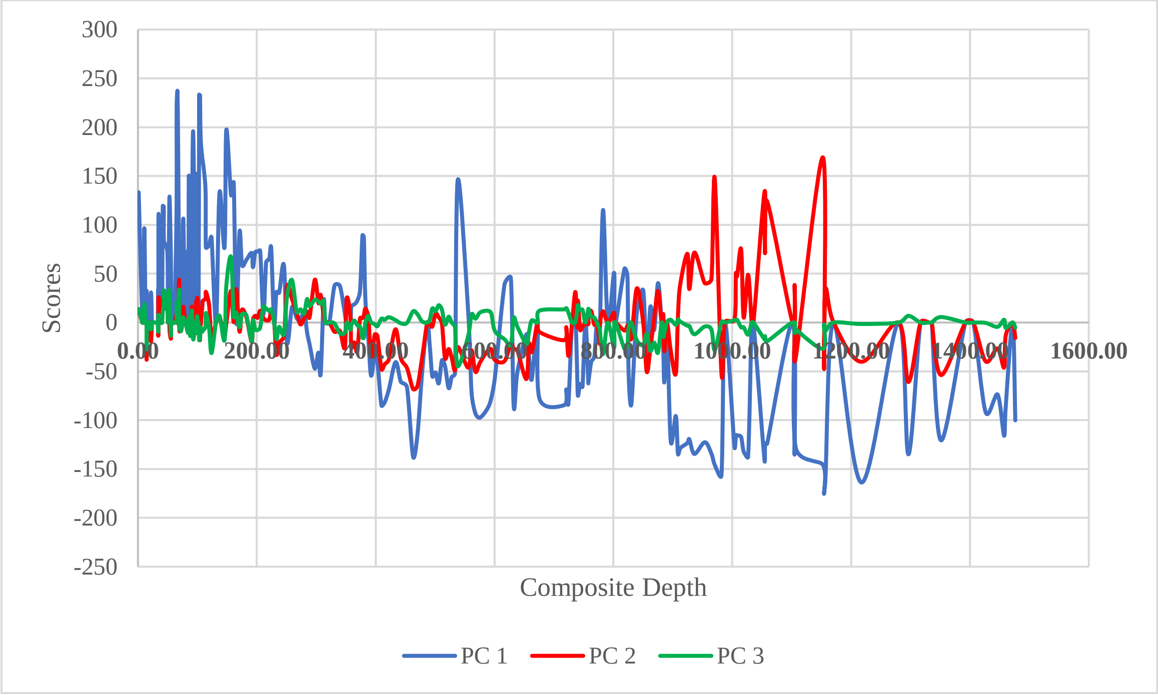

Figure 3: Scores Versus Composite Depth for PCs one, two, and three.

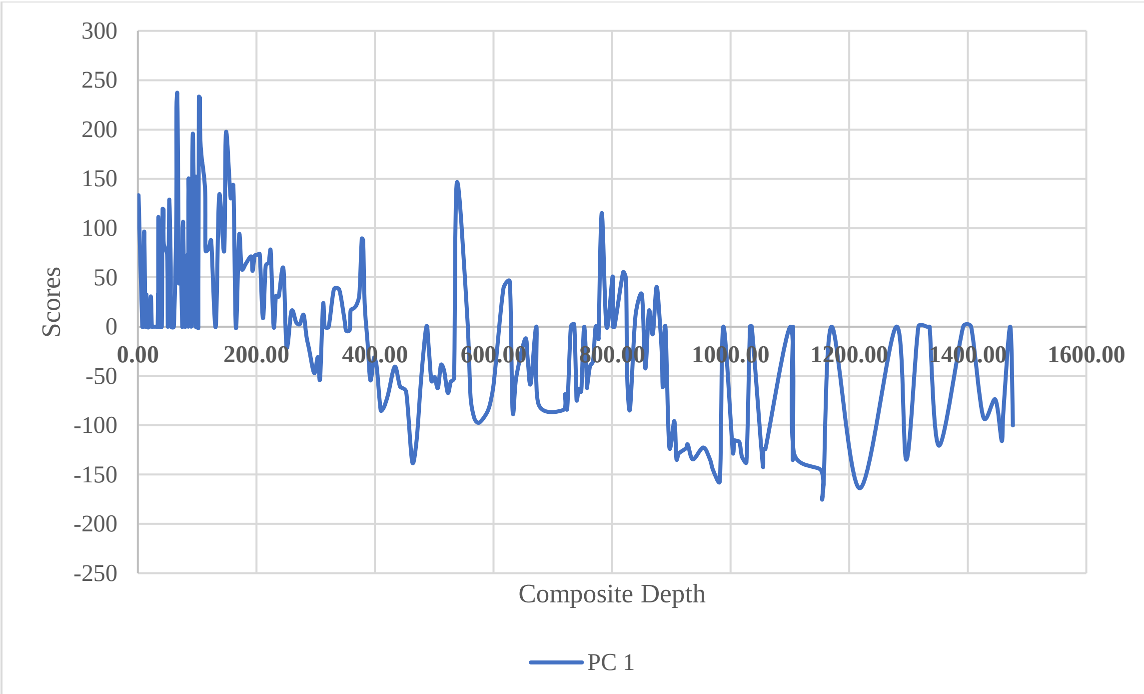

Figure 4: Scores Versus Composite Depth for PC one.

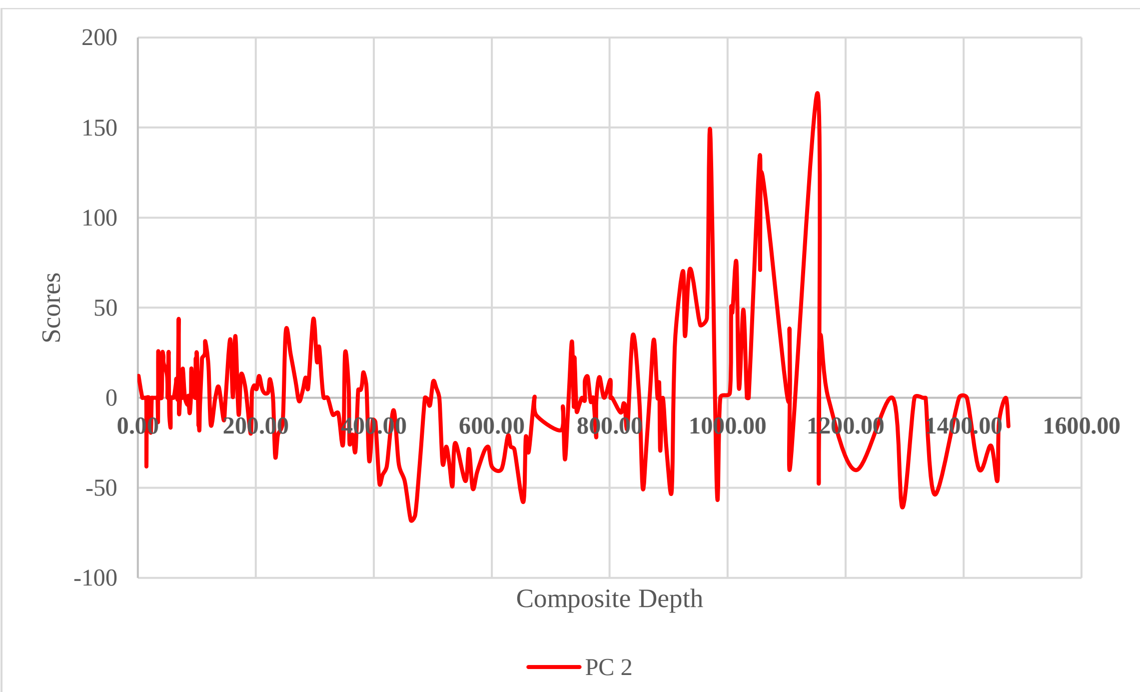

Figure 5: Scores Versus Composite Depth for PC two.

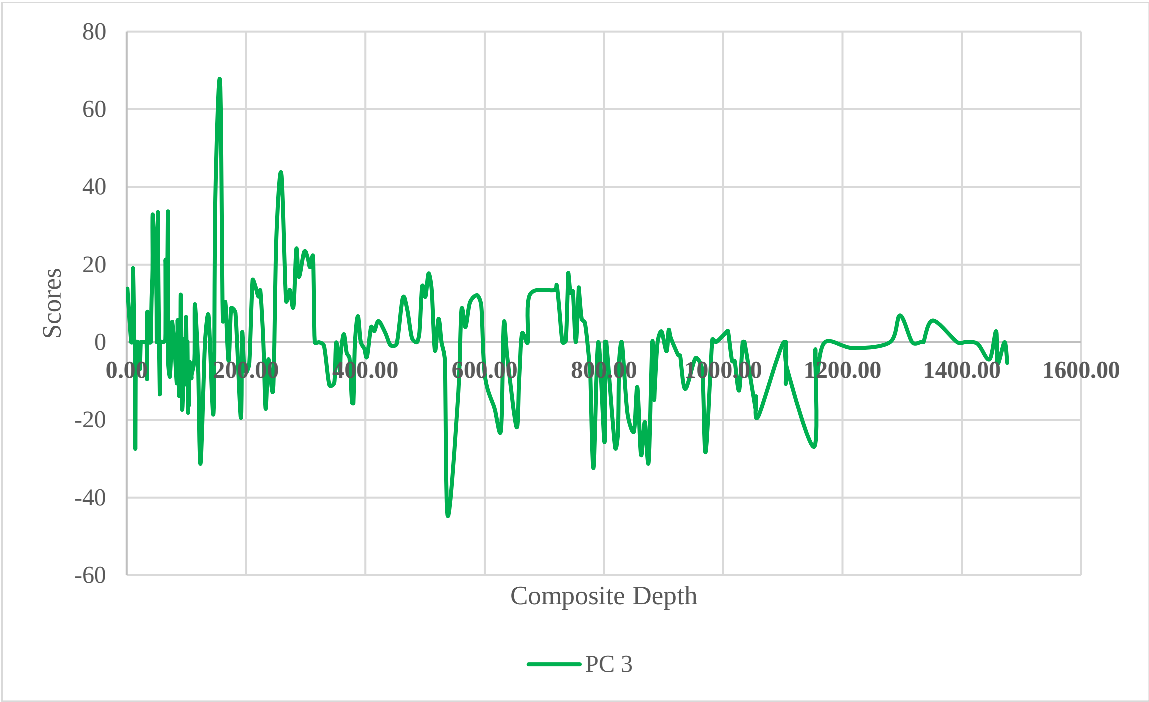

Figure 6: Scores Versus Composite Depth for PC three.

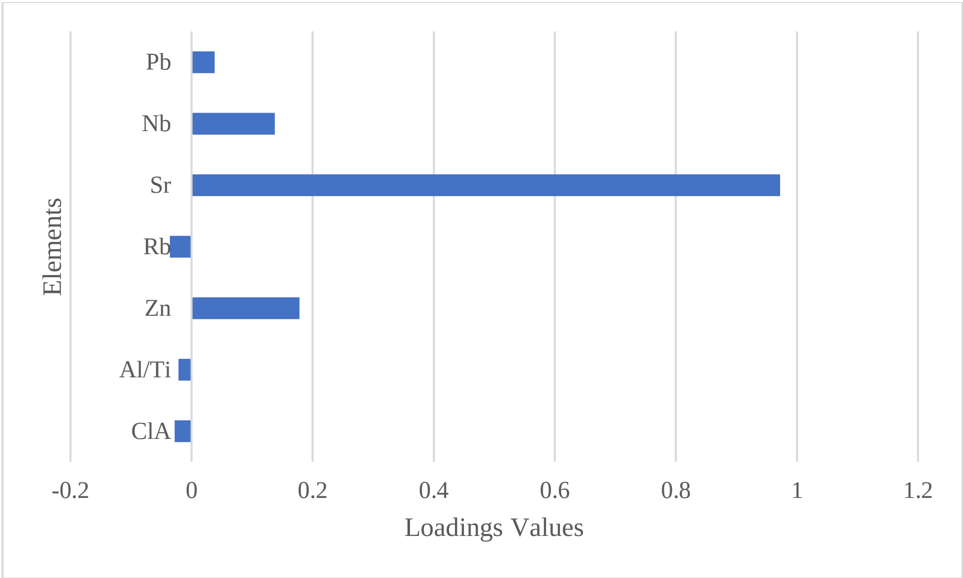

Figure 7: Loadings Plot for PC one. Strontium shows the highest loading.

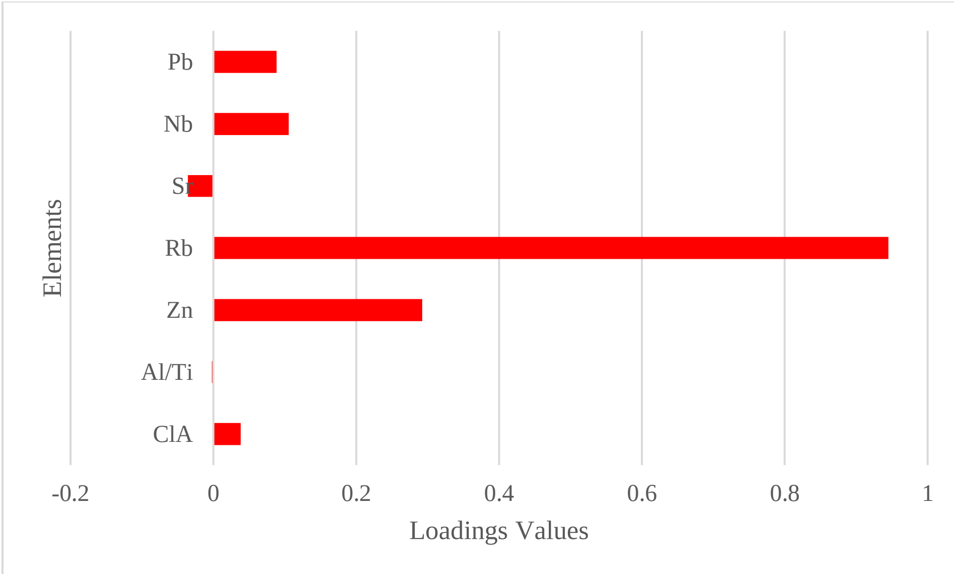

Figure 8: Loadings Plot for PC two. Rubidium shows the highest loading.

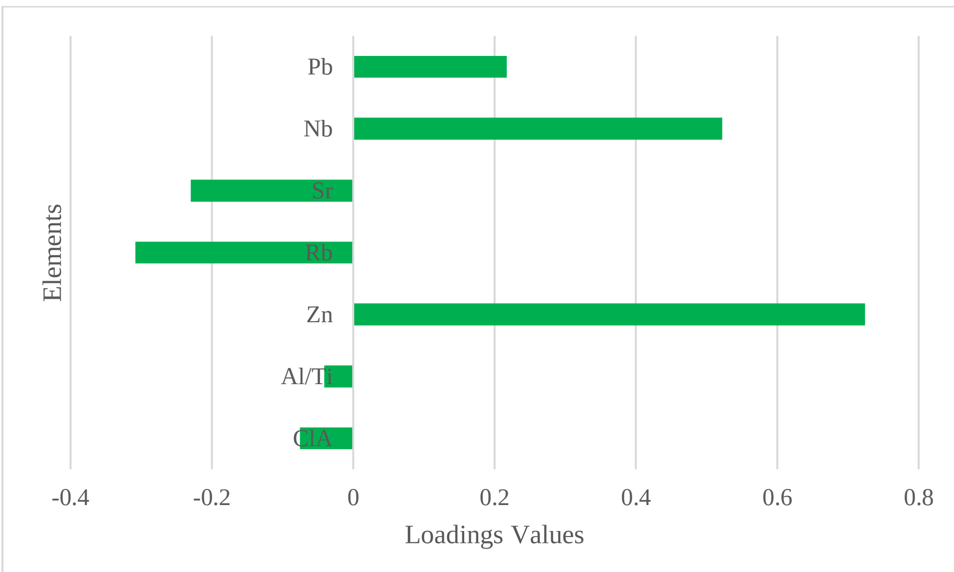

Figure 9: Loadings Plot for PC three. Niobium and Zinc show the highest loading.

Table1: Source Terrane Chemical Data (After Roser and Pyne, 1989)

Source Terrain	AL203/Ti02	Nb	Sr	Zn	CIA	Rb	Pb (ppb)
McMurdo Volcanic Group (Basic)	3.6	114	970	99	33.9	34	5
McMurdo Volcanic Group (Intermediate)	11	204	951	108	43	98	10
Ferrar Dolerite	19.1	8	144	84	42.4	49	9
Lashly Formation	24	12	147	53	63.7	99	21
Lower Beacon	23.8	5	47	28	64.6	55	14
Basement	22.4	13	516	73	48.7	142	20

Discussion and Conclusions

These data were collected from two separate boreholes CRP2 and CRP3. The formations being examined are dipping, and two boreholes were drilled into them, one up-dip from the other. Because of the dip, the down-dip hole penetrated younger sediments, and the up-dip hole penetrated older sediments. Overlapping portions of the two holes were then matched up to produce a cumulative depth scale. This allowed the individual holes to be shallower while still collecting data for stratigraphically deeper sediments. These sediments originated from and were deposited in the West Antarctic Rift System. The source terranes in this region each have characteristic chemical signatures. The principal components generated each have elements that are most responsible for the variance explained by that PC, thereby defining that PC. The elements that define the PCs to the chemical signatures were matched to the source rocks to identify the provenance of the sediments in boreholes CRP2 and CRP3. The most important PCs were one, two, and three, and as such these were the PCs that were studied.

PC one was defined by the importance of Strontium. Strontium is most prevalent in the McMurdo Volcanic Group. When PC ones scores are plotted against depth (Figure 4) the data supports these theories. Eruption of the McMurdo Volcanic Group began in the early Cenozoic. Before that time there was relatively little strontium in the CRP sediment. After that point, there was an increase in strontium, followed by a brief decrease, followed by a massive increase. These results agree with the history of the eruptions that deposited the McMurdo Volcanic Group (Kyle 2013), as well as the history of McMurdo Volcanic Group input at CRP2 and CRP3 derived from other sedimentary records (e.g., sand composition, clay mineralogy; Ehrman and Talarico, 2000).

PC two was defined by the importance of Rubidium. Rubidium is most prevalent in the basement rock. When PC two is plotted against depth (Figure 5) there is an uptick around 1050m where the material from the basement rock makes up a high percentage of the sediment. This increase may be attributed to increased erosion of the continental source rocks that were present prior to the eruption of the McMurdo Volcanic Group.

PC three was most defined by the importance of Niobium and Zinc. Both Niobium and Zinc are most prevalent in the McMurdo Volcanic Group. Though the variation in scores was not as high for PC three as PC one, each followed the same general trend of low scores deepest in the section to medium scores at intermediate depth, to high scores in the upper part of the section. (Figure 6). This similar pattern vs. depth links the two PCs as both indicating provenance of the McMurdo Volcanic Group.

The results of the study indicate that two of the three principal components, PC one and PC three, can be linked to input from the McMurdo Volcanic Group. PC two appears to reflect input from the basement rock in the region. The exact reason for the spike in PC two scores at intermediate depths is unknown. However, it may record an increase in erosion of basement rocks prior to the second major increase in McMurdo Volcanic Group activity.

Recommendations for Future Work

Future research may include testing more boreholes in the area surrounding boreholes CRP-2 and CRP-3 to ascertain if the provenance matches at those sites to that found in this research. If there are differences it could be interesting to find what those differences are and why they exist. Could they be caused by changes in ocean current through time or other factors? Or is PCA simply not always accurate?

Future research may also involve comparing multiple methods of determining provenance to test the hypothesis more thoroughly. Techniques like radioactive dating of minerals to determine their age since formation can help identify their source and is useful especially for igneous rocks.

More testing can be done to identify the limitations of using PCA to identify provenance as well. In the future testing should be run in multiple different environments —terrestrial, marine, freshwater— and should examine different scenarios. For example, does PCA work well in a closed sedimentary environment such as a lagoon where the source material is very limited, but work less well in a place like the Mississippi River delta where sediment from the eastern half of the United States is deposited?

Citations

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Appendix A: Raw Geochemical Data

Composite Olig/Mio Depth	Smoothed CIA	Smoothed Al/Ti	Zn	Rb	Sr	Nb	Pb
				pp		pp	
1.23							
7.48							
9.50	40.1	11.15	117		334		26
10.70							
12.78							
12.83	42.4	12.40	95	80	297	43	15
14.33							
14.56							
15.58							
19.40	41.6	15.01	34	61	247	7	11
21.90							
23.60							
24.57	42.0	16.06	55	72	240	16	22
25.90							
28.60							
28.87							
31.94							
33.45							
34.15							
34.44							
34.67	43.6	19.57	57	78	243	15	19
37.82							
40.40	42.9	16.57	92	108	313	48	19
41.78							
43.42							
43.73	42.6	14.70	98	106	320	50	14
49.48	43.0	15.16	102	101	318	49	29
50.44	43.1	15.22	105	94	281	48	37
50.75	42.7	15.37	87	94	274	42	24
52.25							
53.18							
55.52	42.2	15.17	105	101	287	63	18
55.90	42.4	15.28	86	73	329	55	26
60.72	43.0	15.26	55	76	270	21	18
64.85							
65.15							
66.48	43.8	12.33	81	94	314	42	17

67.64	43.5	11.09	117	85	418	70	22
69.26	44.5	11.68	99	80	436	75	19
69.70	44.4	12.44	90	81	376	65	14
72.43	44.6	14.38	113	116	244	22	69
75.15	45.1	16.00	65	81	271	24	24
75.60	45.3	17.18	67	93	271	24	18
76.40							
79.84	43.9	15.81	83	92	302	30	45
84.20	43.6	16.15	87	98	309	29	51
85.15							
85.57	43.1	15.23	68	86	282	20	17
87.80							
89.94	43.4	16.73	87	83	352	40	48
90.75	43.9	16.45	60	83	277	20	20
92.92							
97.19	44.4	16.45	90	97	272	22	48
97.80	44.6	15.22	92	92	401	33	10
98.13							
98.20	44.7	13.55	83	95	358	35	23
98.59							
99.55	45.1	13.92	88	106	310	39	17
100.60							
101.92	44.0	13.00	93	106	323	38	41
102.92	43.5	12.13	87	106	327	40	19
103.33							
104.37	42.1	10.08	81	73	435	49	12
105.40	41.8	9.46	81	74	401	47	12
108.57	42.4	10.27	81	70	438	53	10
108.90	42.7	11.00	88	81	394	51	11
113.64	43.1	11.90	88	105	370	45	16
114.35	44.0	13.04	92	107	370	43	15
119.67	44.4	14.68	91	109	340	40	16
123.78	44.4	16.98	95	113	279	37	16
131.38	44.3	16.88	79	105	285	28	16
137.24	44.3	16.52	46	82	300	18	14
145.69							
148.64	43.1	15.38	88	89	335	53	12
156.65	43.2	12.94	55	81	287	25	12
161.17	43.3	12.19	115	70	391	71	49
165.40	44.5	13.08	125	98	317	113	15
170.84	44.9	11.81	91	83	345	47	13
175.20	45.7	13.09	84	118	203	22	18
182.42	44.0	13.39	72	79	299	31	12

191.40	43.8	15.43	84	97	262	34	14
193.52	42.4	15.41	81	90	268	34	14
197.21	42.1	16.17	55	74	282	16	12
201.45	41.6	16.76	81	89	262	21	14
205.62	43.3	17.40	76	95	279	21	14
211.05	43.8	16.68	76	93	280	19	15
215.67	44.2	15.99	81	99	280	20	15
220.95	44.5	14.83	75	89	212	34	13
224.10	44.7	13.64	92	84	264	27	14
229.16	44.6	13.36	86	86	268	33	14
232.99	43.6	14.53	92	92	279	36	14
237.64							
245.60	42.7	17.30	42	63	243	15	12
250.94	43.5	19.12	55	71	239	25	11
259.22	42.7	18.81	58	78	268	22	13
267.20	43.7	18.14	98	116	180	24	16
273.38	44.4	17.29	97	97	213	39	67
279.62	45.2	17.11	74	95	209	27	15
284.49	44.9	16.26	68	84	207	34	13
288.71	46.5	17.06	72	90	217	28	14
297.60	47.9	17.34	81	93	192	35	14
303.68	48.7	17.97	71	90	182	29	14
307.39	50.0	18.40	92	124	155	19	18
312.45	49.8	18.91	82	102	172	25	16
315.32	48.5	17.68	82	111	151	16	17
321.94	47.7	16.18	82	89	224	41	15
330.80							
339.76							
348.09	44.3	15.89	68	79	245	20	13
351.32	46.1	17.27	60	83	247	15	14
357.42	45.9	18.36	48	68	220	13	12
358.96	45.1	17.45	76	112	203	11	15
364.04	44.7	16.56	61	97	206	11	13
368.98	43.8	15.46	59	65	225	12	13
373.68	42.7	14.91	67	68	226	12	13
377.75	41.5	14.47	60	61	231	11	11
380.08	42.1	14.82	72	93	240	13	15
382.63	43.2	15.34	75	94	298	13	16
387.61	45.3	15.73	75	97	296	14	16
392.31	44.9	15.82	77	101	231	14	17
398.44	45.9	16.48	71	93	190	14	15
402.87	47.0	17.30	42	58	156	8	11

409.71	46.5	17.85	54	79	178	9	13
415.04	45.7	18.64	48	79	170	9	15
422.16	46.3	19.21	36	46	126	4	9
433.49	47.0	19.36	37	51	129	5	9
442.47	46.6	19.40	44	54	141	6	12
452.67	46.5	19.48	58	83	168	9	14
462.88	45.4	19.63	40	57	150	6	10
470.28	43.9	19.11	36	48	145	5	9
478.18	42.3	18.96	24	27	74	2	5
486.76	40.7	18.49	27	30	96	3	6
490.87	41.7	17.98	44	57	159	7	11
495.36							
500.76	46.3	17.83	65	88	185	10	14
506.16	47.9	17.62	68	82	151	10	14
511.38	50.0	17.31	71	95	155	10	15
516.70	45.8	17.73	74	90	143	9	14
522.85	44.9	18.29	72	85	167	11	14
528.03	43.5	18.30	44	57	166	5	9
533.48	43.3	19.17	49	64	142	6	12
538.15	44.4	20.03	43	57	155	5	10
555.38	48.8	19.83	36	46	160	3	8
561.34	49.9	19.62	53	73	361	6	12
567.83	46.4	19.55	44	49	226	4	8
575.50	45.8	18.77	51	62	137	6	9
587.83	44.6	18.33	33	44	118	4	7
594.43	43.8	18.41	41	51	112	6	8
600.57	43.3	18.72	49	61	120	7	10
616.78	46.0	18.62	50	63	131	7	10
627.45	47.4	18.70	32	58	156	6	9
632.19	48.5	19.03	49	55	251	6	10
638.40	49.2	19.29	51	74	258	7	10
653.56	48.8	19.14	44	65	125	6	8
657.77	50.0	19.38	43	65	160	5	10
662.70	48.2	19.55	24	42	203	4	7
672.36	47.1	19.00	42	73	178	7	10
675.84	46.8	18.91	47	62	152	6	10
717.23							
720.77	47.5	18.68	54	79	129	13	16
724.34	47.6	18.43	52	71	123	12	13
730.48	48.0	18.75	61	82	138	14	16
736.09	48.0	18.65	43	57	126	12	11
739.18							
740.29	48.6	18.98	75	118	209	18	20

743.97	48.8	19.11	63	82	152	14	15
748.00	48.7	19.45	72	107	130	14	21
752.99	48.5	19.64	60	80	144	13	16
757.83	49.0	20.00	61	83	141	13	16
757.95							
762.76	49.7	20.43	64	85	144	13	17
767.97	50.0	20.29	70	95	145	11	17
772.32	50.2	20.21	67	99	167	11	19
777.21		19.96	63	86	173	10	17
777.29							
782.60		20.25	49	71	198	8	14
790.60		20.68	54	90	198	10	18
801.07		21.29	67	105	327	11	19
801.36							
804.09	52.6	21.78	57	104	263	10	18
818.65							
823.58							
825.60	53.1	20.22	52	87	268	8	15
830.23	53.6	19.97	55	91	260	9	16
839.44	51.5	19.89	48	89	158	9	13
850.20	51.5	19.97	42	77	127	7	10
856.06	49.9	19.43	64	127	221	10	16
862.20	50.3	19.40	53	94	245	8	14
868.66	51.0	19.38	29	47	171	6	7
875.08	53.9	19.35	33	72	231	7	11
881.16	54.0	19.17	46	100	205	9	14
884.04	56.0	19.85	58	127	253	9	17
885.77							
890.00	55.2	18.81	49	102	182	8	13
896.44	53.8	18.16	32	67	152	7	9
904.98							
908.60	52.4	18.33	30	66	90	7	9
912.37	54.1	19.24	25	44	117	5	5
924.50	55.7	20.84	41	99	76	6	10
927.80	56.3	21.24	50	130	81	8	15
936.30	57.7	22.18	58	161	86	9	16
953.76	56.1	21.84	46	127	91	8	14
964.95	55.8	21.15	46	166	77	8	15
970.53	55.4	20.95	48	133	88	7	12
981.80	52.5	20.40	42	139	77	8	11
987.62	52.2	19.42	54	244	67	8	12
1003.75	53.5	18.98	12	47	57	4	5
1006.14							

1008.13	53.1	18.61	39	96	83	8	10
1014.91	56.8	19.22	60	140	93	9	14
1019.20	55.7	18.53	58	137	93	10	14
1026.68	55.8	18.48	58	166	92	11	16
1032.66	55.2	16.92	32	101	80	7	7
1035.76	56.6	17.99	37	145	75	8	11
1054.21							
1055.10							
1058.69	60.0	20.62	59	226	70	10	23
1101.44	61.1	22.29	49	165	88	7	11
1104.82	59.2	21.08	61	217	87	9	14
1105.38							
1106.78		17.89	36	135	77	7	9
1152.42							
1154.38		18.31	17	63	86	4	6
1156.77		18.23	62	264	66	8	17
1170.59		18.79	6	56	39	3	5
1217.77		19.84	31	131	53	6	7
1279.49							
1296.42		19.54	12	59	50	3	5
1316.80							
1330.92		20.61	22	35	77	3	5
1335.40							
1335.76							
1351.59							
1392.34							
1405.70	55.3	20.17	27	41	91	4	6
1426.33							
1446.36							
1457.41	53.2	19.10	33	55	120	4	8
1460.10	52.8	19.95	38	68	138	5	8
1471.70	53.3	20.54	28	49	96	4	6
1476.20	53.4	20.27	38	81	125	5	8
1476.29							
1483.87		19.31	34	80	112	4	7

Appendix B: Percent Variances

PC	% variance
PC1	85.257
PC2	11.411
PC3	2.0897
PC4	0.75175
PC5	0.38478
PC6	0.088251
PC7	0.017302

Appendix C: Scores

PC 1	PC 2	PC 3
133.33	12.2	13.802
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
96.548	0.012169	19.082
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
32.604	-38.17	-27.468
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
30.768	-19.45	-7.0245
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
33.452	-13.62	-9.5542
-6.24E-14	-3.57E-14	-1.03E-14
111.29	25.908	7.8669
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
119.38	25.283	11.279
118.74	23.036	18.866
83.714	19.231	32.907
72.386	12.421	15.543
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
90.663	25.496	33.145
128.32	-8.1515	15.908
60.317	-16.533	-13.453
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
109.98	8.6617	0.52498
221.91	10.34	21.261
236.92	0.004832	7.4889
175.36	-1.0322	8.1173
45.986	43.834	33.711
63.458	-7.9946	-5.3005

63.122	3.4036	-8.9204
-6.24E-14	-3.57E-14	-1.03E-14
98.072	8.9947	5.0146
105.47	15.996	5.2424
-6.24E-14	-3.57E-14	-1.03E-14
73.763	-3.9024	-10.625
-6.24E-14	-3.57E-14	-1.03E-14
149.21	1.1654	5.0728
67.649	-8.6042	-13.804
-6.24E-14	-3.57E-14	-1.03E-14
68.957	16.282	11.847
195	5.328	-17.283
-6.24E-14	-3.57E-14	-1.03E-14
152.29	8.4392	-10.917
-6.24E-14	-3.57E-14	-1.03E-14
106.42	21.921	1.0829
-6.24E-14	-3.57E-14	-1.03E-14
120.77	24.894	6.5295
123.06	21.244	-2.3976
-6.24E-14	-3.57E-14	-1.03E-14
229.25	-15.284	-18.014
195.9	-13.341	-11.505
232.73	-17.97	-16.153
190.54	-4.0643	-5.2446
165.68	19.297	-9.2473
165.95	22.089	-8.3432
136.11	24.546	-4.2369
76.913	31.362	9.7842
78.948	17.957	-5.4052
87.034	-15.194	-31.303
-6.24E-14	-3.57E-14	-1.03E-14
133.1	5.9149	6.8992
77.032	-12.515	-18.037
196.99	-0.96766	37.003
130.25	32.529	67.037
142.81	0.29787	5.7183
-1.0608	34.249	10.4
92.596	-9.201	-4.8093
58.562	13.124	8.7662
64.153	5.3632	7.4803
71.145	-19.947	-19.478
56.559	3.2306	2.3834
71.918	6.892	-7.1506

72.727	4.8649	-7.5991
73.543	12.119	-5.3081
8.5898	4.6646	15.96
61.453	2.4095	14.461
65.035	3.0297	11.731
76.998	10.334	13.293
-6.24E-14	-3.57E-14	-1.03E-14
31.128	-32.829	-17.152
30.545	-20.333	-4.4135
58.714	-14.05	-12.124
-20.709	37.224	26.999
15.887	23.913	43.448
4.3215	9.6105	10.707
2.619	-1.9155	13.492
11.988	4.0813	9.1709
-9.9031	11.235	24.049
-22.162	5.2315	16.809
-47.167	43.817	23.267
-30.882	19.941	21.597
-52.763	28.291	19.311
22.426	7.3158	22.066
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
37.842	-9.4989	-0.9494
37.486	-8.5029	-11.024
9.268	-25.615	-10.392
-3.9767	24.784	-0.07301
-3.2381	5.9257	-7.3682
16.22	-25.503	-2.6764
18.553	-20.406	2.0686
22.248	-29.574	-2.8396
32.385	4.4358	-4.2336
89.271	4.3083	-15.585
87.289	7.3998	-15.703
24.352	14.167	-0.30695
-16.409	6.1836	6.7001
-54.398	-35.095	0.18569
-31.412	-12.27	-1.6842
-40.179	-13.593	-3.7291
-84.851	-47.742	3.8872
-81.821	-42.701	2.8429
-68.753	-37.894	5.4328
-40.563	-6.877	2.4281

-60.872	-36.775	-0.81166
-66.244	-46.52	-0.38861
-137.17	-68.057	11.405
-115.13	-65.001	8.4764
-51.094	-35.873	1.1037
-6.24E-14	-3.57E-14	-1.03E-14
-22.789	-0.61358	2.654
-55.133	-4.1246	14.379
-51.193	9.0626	11.694
-62.212	5.2899	17.728
-38.766	-0.70503	13.396
-44.697	-36.443	-2.133
-67.154	-27.145	5.9983
-55.594	-36.222	-0.25074
-52.053	-49.06	-4.8799
145.96	-25.07	-44.726
13.644	-46.238	-14.463
-71.761	-28.439	8.3888
-93.101	-50.462	3.8993
-97.427	-41.025	10.232
-88.363	-29.261	12.086
-77.635	-27.369	9.4654
-56.574	-38.395	-8.6241
38.929	-39.533	-17.096
45.518	-21.115	-22.658
-84.914	-27.195	4.6917
-51.163	-28.625	-4.2641
-12.119	-57.896	-21.858
-33.766	-21.904	-10.314
-57.883	-30.02	2.1803
-6.24E-14	-3.57E-14	-1.03E-14
-78.433	-9.79	12.208
-84.584	-18.085	13.435
-68.421	-5.1063	14.766
-82.858	-34.215	10.071
-6.24E-14	-3.57E-14	-1.03E-14
2.4853	31.256	0.38837
-54.521	-5.0817	12.705
-74.986	22.487	17.865
-62.865	-7.5917	12.684
-65.733	-4.3386	13.12
-6.24E-14	-3.57E-14	-1.03E-14
-62.344	-1.5646	14.133

-60.944	9.4043	14.103
-40.162	11.702	6.0628
-34.695	-2.3661	5.0832
-6.24E-14	-3.57E-14	-1.03E-14
-12.739	-22.007	-7.8836
-12.115	-2.0283	-8.2272
115.24	11.515	-32.369
-6.24E-14	-3.57E-14	-1.03E-14
50.934	9.9554	-25.77
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
55.148	-8.2024	-26.966
47.928	-3.0452	-23.477
-52.471	-3.6712	-4.9798
-83.638	-16.129	-0.19946
10.567	34.965	-18.277
32.77	-0.66541	-23.088
-42.319	-50.243	-11.585
16.036	-27.032	-29.015
-7.5452	4.6385	-20.565
40.331	32.28	-30.76
-6.24E-14	-3.57E-14	-1.03E-14
-29.645	8.0834	-14.539
-60.816	-29.395	-10.42
-6.24E-14	-3.57E-14	-1.03E-14
-121.38	-28.756	2.7864
-95.722	-52.475	-2.3324
-134.47	6.2482	3.1347
-128.68	38.667	1.0106
-123.4	70.364	-3.3115
-119.61	34.207	-3.486
-134.57	71.637	-12.032
-122.56	40.261	-4.0665
-134.35	44.477	-7.1892
-145.66	147.64	-28.311
-156.6	-51.419	0.64781
-6.24E-14	-3.57E-14	-1.03E-14
-127.52	2.6932	2.3346
-115.46	50.651	2.7611
-115.53	47.296	2.8713
-117.34	75.019	-4.8939
-132.13	5.1916	-4.8526
-137.47	48.918	-12.414

-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-140.75	133.46	-17.029
-123.77	70.917	-13.916
-124.01	124	-19.147
-6.24E-14	-3.57E-14	-1.03E-14
-135.29	38.459	-10.749
-6.24E-14	-3.57E-14	-1.03E-14
-127.86	-36.034	-6.6042
-145.57	169.16	-26.938
-175.45	-44.375	-2.3706
-159.62	33.791	-8.6578
-6.24E-14	-3.57E-14	-1.03E-14
-163.81	-40.181	-1.5085
-6.24E-14	-3.57E-14	-1.03E-14
-134.93	-60.904	6.8903
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-120.69	-53.765	5.5833
-6.24E-14	-3.57E-14	-1.03E-14
-6.24E-14	-3.57E-14	-1.03E-14
-91.771	-39.723	-0.41729
-73.719	-26.535	-4.4247
-115.89	-46.171	2.8266
-86.851	-13.763	-5.506
-6.24E-14	-3.57E-14	-1.03E-14
-100.15	-15.845	-5.3332

Appendix D: Loadings Plot

Element	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7
CIA	-0.02776	0.038418	-0.07551	-0.04193	0.081101	0.96148	-0.24347
Al/Ti	-0.02169	-0.00216	-0.04078	0.048833	0.016914	0.24203	0.96779
Zn	0.17829	0.29247	0.72435	0.31756	-0.49582	0.10633	0.001218
Rb	-0.03612	0.94487	-0.30849	-0.07104	0.033854	-0.06695	0.008034
Sr	0.97225	-0.03585	-0.22981	0.018387	0.007433	0.013546	0.007582
Nb	0.13766	0.10532	0.52228	-0.72667	0.40707	-0.01067	0.057546
Pb	0.038035	0.088396	0.21725	0.60131	0.76183	-0.02998	-0.02595

Appendix E: Source Terranes

Source Terrain	AL203/Ti02	Nb	Sr	Zn	CIA	Rb	Pb (ppb)
McMurdo Volcanic Group (Basic)	3.6	114	970	99	33.9	34	5
McMurdo Volcanic Group (Intermediate)	11	204	951	108	43	98	10
Ferrar Dolerite	19.1	8	144	84	42.4	49	9
Lashly Formation	24	12	147	53	63.7	99	21
Lower Beacon	23.8	5	47	28	64.6	55	14
Basement	22.4	13	516	73	48.7	142	20